

High-Speed Imaging of the First Kink Mode Instability in a Magnetoplasmadynamic Thruster

IEPC-2013-###

*Presented at the 33rd International Electric Propulsion Conference,
Washington D.C., United States of America
October 6-10, 2013*

Jonathan A. Walker¹, Samuel Langendorf², and Mitchell L. R. Walker³

High-Power Electric Propulsion Laboratory, Georgia Institute of Technology, Atlanta, GA, 30332, USA

Kurt Polzin⁴ and Adam Kimberlin⁵

NASA Marshall Space Flight Center, Huntsville, AL, 35812, USA

One of the biggest challenges to efficient magnetoplasmadynamic thruster (MPDT) operation is the onset of high-frequency voltage oscillations as the discharge current is increased above a threshold value. The onset regime is closely related to magnetohydrodynamic instabilities known as kink modes. This work documents direct observation of the formation and quasi-steady state behavior of an argon discharge plasma in a MPDT operating at discharge currents of 8 to 10 kA for a pulse length of approximately 4 ms. A high-speed camera images the quasi-steady-state operation of the thruster at 26,143 fps with a frame exposure time of 10 μ s. A 0.9 neutral density filter and 488-nm argon line filter with a 10-nm bandwidth are used on separate trials to capture the time evolution of the discharge plasma. Frame-by-frame analysis of the power flux incident on the CCD sensor shows both the initial discharge plasma formation process and the steady-state behavior of the discharge plasma. Light intensity levels on the order of 4-6 W/m² indicate radial and azimuthal asymmetries in the concentration of argon plasma in the discharge channel. The plasma concentration exhibits characteristics that suggest the presence of a helical plasma column. This helical behavior has been observed in previous experiments that characterize plasma kink mode instabilities indirectly. Therefore, the direct imaging of these plasma kink modes further supports the link between MPDT onset behavior and the excitation of the magnetohydrodynamic instabilities.

I. Introduction

The magnetoplasmadynamic thruster (MPDT) offers both high mass utilization and high thrust density compared to traditional types of electric propulsion such as Hall effect thrusters or ion-gridded thrusters. MPDT operation at power levels conducive to both high thrust density and I_{sp} leads to unstable thruster operation and is marked by the onset of high-frequency voltage fluctuations [1-4]. This unstable operational regime is referred to as “onset”. During onset the MPDT suffers increased power deposition into the anode walls, with high anode erosion rates and poor thruster efficiency, characteristics typical of this operating regime. The leading explanation for the onset phenomena points to the existence of plasma instabilities that are excited during operation [4].

A pulse forming network (PFN) provides power levels, approximately 1 MW in a current regime of 9 kA for 3- 4 ms, necessary to achieve to high thrust density and I_{sp} [5]. To the knowledge of the authors, time-resolved global photographs of the overall discharge plasma behavior during a complete single pulse at frame rates capable of capturing the lower-order kink mode dynamics have not previously been captured. While many experiments have

¹ Graduate Research Assistant, School of Aerospace Engineering, jwalker30@gatech.edu

² Graduate Research Assistant, School of Aerospace Engineering, slangendorf3@gatech.edu

³ Associate Professor, School of Aerospace Engineering, mitchell.walker@ae.gatech.edu

⁴ Propulsion Research Engineer, Propulsion Systems Department, kurt.a.polzin@nasa.gov

⁵ Research Engineer, Propulsion Systems Department, adam.c.kimberlin@nasa.gov

used radial optical measurements and Abel inversion techniques to infer on-axis plasma characteristics (c.f. Ref. [4]), direct spatially-resolved observation of global plasma emission should reveal details otherwise lost using radial measurement techniques. The presented work includes a time evolution of the plasma topology within the discharge chamber of the MPDT linked with the discharge current pulse trace. In doing so, a frame by frame optical image analysis is directly correlated to different thruster operating regimes, transient and steady state operation.

II. Experimental Apparatus

A. Vacuum Facilities

All of the experiments are performed in the vacuum test facility 2 (VTF-2) at Georgia Tech. VTF-2 is a stainless steel chamber 9.2 m long and 4.9 m in diameter. It is pumped to rough vacuum with one 3800 CFM blower and one 495 CFM rotary-vane pump. Ten liquid nitrogen cooled shrouds surrounding CVI TMI-1200 re-entrant cryopumps with a combined pumping speed of 350,000 l/s on xenon bring the chamber to a base pressure of 6×10^{-9} torr- N_2 . A Stirling Cryogenics SPC-8 RL special closed-looped nitrogen liquefaction system supplies liquid nitrogen to the cryopump shrouds. Two ionization gauges, a Varian 571 and a UHV-24, are mounted on either side of the chamber and are used to measure pressure

B. Mass Flow System.

The thruster was designed to operate with mass flow rates greater than 0.3 g/s. A pulsed gas feed system is employed to maintain the high vacuum condition at such a large mass flow rate. The propellant feed system is based on the pulse gas system employed at NASA Glenn[1]. The system features a 117 ft³ air, 3000 psi scuba tank as a propellant plenum and an Omega SV251 3-way solenoid valve. A 0.0625-in stainless steel tube serves as a choke point. The plenum is connected to a bottle of 99.995% purity argon and maintained at a constant pressure during firing. Adjustment of the plenum pressure allowed for control of the mass flow during thruster operation. Based on calibration methods outlined in[1], a mass flow rate uncertainty of less than $\pm 5\%$ is expected. By using 1-second gas pulses, the background pressure during operation is in the 7.8×10^{-6} - 1.5×10^{-5} torr-Ar range.

C. Diagnostics

A Phantom v7.2 high-speed camera images the thruster during operation. The camera is mounted outside the vacuum chamber and is aligned axially with the MPDT. A 12-in Lexan viewport provides optical access. The frame rate is 26143 fps, the CCD resolution for this frame rate is 256 x 256 pixels, and the frame exposure time is 10 μ s. A 0.9 neutral density filter and 488-nm argon line filter with a 10-nm bandwidth are used separately to capture different optical characteristics of the discharge. Simultaneous current and voltage data traces are captured using a 500 MHz DPO7054 oscilloscope, two frequency compensated Tektronix P6015A frequency-compensated voltage probes, and a Pearson 1330 current transformer.

D. Thruster and Pulse Forming Network

The thruster features a design similar to the MW-class thruster previously developed and tested at NASA Glenn Research Center[1]. The thruster is a self-field design, with a 3/4-in thoriated tungsten central cathode, a 2.5-in wide discharge channel, and a 3-in thick stainless steel anode. The thruster is designed to handle pulsed power loads above 1 MW. Power is supplied to the MPDT at current levels between 8-10 kA for approximately 4ms. The pulse is generated using a Raleigh Line pulse forming network (PFN). The PFN consists of seven 360 μ F, 10 kV capacitors with a combined energy storage of 126 kJ.

III. References

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